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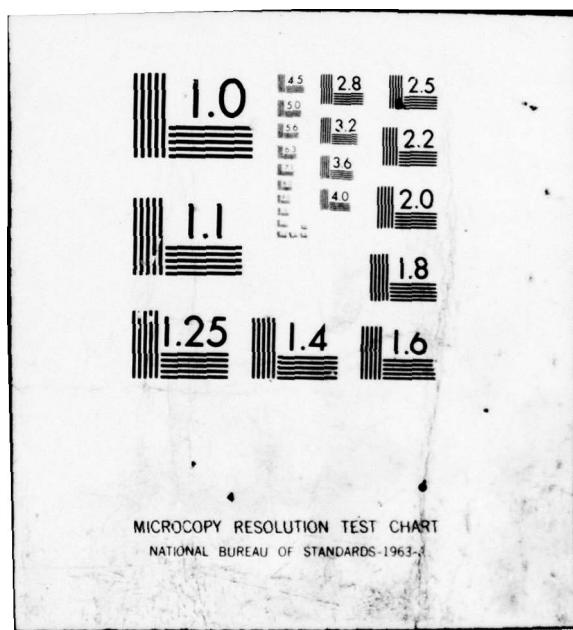
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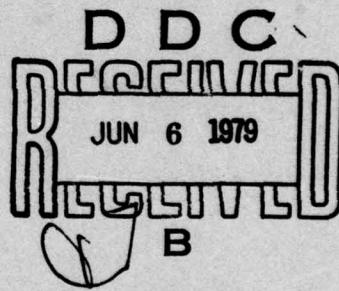
NRL Report 8312 ✓

Initial Design for NTS Time Transfer Receiver

O. JAY OAKS, JR., JAMES A. BUISSON, AND THOMAS B. McCASKILL

*Space Applications Branch
Space Systems Division*

May 16, 1979 ✓



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A Time Transfer Receiver (TTR) was designed to utilize the Navigation Technology Satellites (NTS) for making precise time comparisons between a master station and remotely located stations. The receiver processes a 335-MHz sidetone ranging signal from an NTS satellite using a microcomputer-controlled processor. The receiver-processed data are then compared to data obtained at the master station to arrive at a time comparison. The nominal accuracy of the results is approximately 200 ns.		

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INITIAL DESIGN FOR NTS TIME TRANSFER RECEIVER

INTRODUCTION

The development of the Navigation Technology Satellite Time Transfer Receiver (NTS/TTR) resulted from a requirement that the NASA Goddard Laser Ranging Network have a worldwide clock synchronization of at least $1\text{-}\mu\text{s}$ accuracy. The Naval Research Laboratory had conducted time transfer experiments [1] using the NTS satellites and obtained results with an accuracy of several hundred nanoseconds. Since there was no other system available that could guarantee this accuracy, NASA sponsored a joint effort by the Naval Research Laboratory, the Naval Surface Weapons Center Dahlgren Laboratory, and the Johns Hopkins University Applied Physics Laboratory to design, develop, and test the NTS/TTR.

NAVIGATION TECHNOLOGY SATELLITES

The Naval Research Laboratory has launched four advanced research technology satellites for the purpose of studying onboard clock stability, navigation by satellite, and satellite orbit determination. The first two satellites were named TIMATION I and TIMATION II and carried quartz crystal oscillators. The third was named NTS-1 and carried quartz crystal and rubidium oscillators. The fourth, named NTS-2, was the first satellite in the NAVSTAR Global Positioning System (GPS) constellation and carried two cesium oscillators [2]. A fifth satellite NTS-3 is planned and will have a hydrogen maser standard oscillator [3]. Table 1 presents some pertinent information on the NRL research technology satellites. The NTS/TTR was designed to operate with any of the NTS satellites.

TIME TRANSFER METHOD

To perform a time transfer, satellite data are taken at the NRL central station and a remote station. At the NRL station, data are processed from the satellite to give a measurement which includes the propagation delay in the signal plus the difference between the satellite clock and the central ground-station clock. The propagation delay is subtracted out by knowing the exact locations of the satellite and the station. This leaves the difference between the satellite clock and the central ground-station clock. A similar measurement is made at the remote station using an NTS/TTR. If the satellite being used has a quartz crystal oscillator, then the remote measurement is updated for the drift of the satellite clock during the time between the two measurements. The two differences between the ground clocks and the satellite clock are then compared to obtain the difference between the ground clocks. The NRL central-station clock is linked to the U.S. Naval Observatory master

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Table 1 — NRL Technology Satellites

Satellite	Launch Date	Altitude (n.mi.)	Inclination (deg)	Eccentricity	Weight (kg)	Power (W)	Frequency	Oscillator	$\Delta f/f$ per day (pp 10^{-3})	Range Error (m/day)
T-I	5-31-67	500	70	0.0008	40	85	6	UHF	Qtz	300
T-II	8-30-69	500	70	0.002	55	125	18	VHF/UHF	Qtz	100
T-III or NTS-1	6-14-74	7,400	125	0.007	295	650	100	UHF/L band	Qtz/Rb	5-10
NTS-2	6-23-77	10,900	63	0.0004	430	950	445*	UHF/L,L ₁ ,L ₂	Qtz/Cs	2
NTS-3	1982	10,900	63	0.001	490	1080	475*	UHF&L,L ₁ ,L ₂	Cs/H ₂	0.1

*Beginning of Life (BOL)

clock number one (USNOMC1) by weekly portable clock measurements, and taking this into account, the final difference between USNOMC1 and the remote-station clock is obtained. Figure 1 is a visual concept of the time transfer technique, and a more detailed explanation can be found in Ref. 1.

RECEIVER FUNCTIONAL DESCRIPTION

The final output of the NTS/TTR is a measurement of the range delay of the signal from the satellite expressed in milliseconds to six decimal places for nanosecond resolution. This measurement is obtained using the technique of sidetone ranging. In sidetone ranging, phase comparisons are made between satellite-transmitted tones and receiver-generated tones of the same frequency. Both sets of tones are derived from very stable frequency sources so that the phase differences represent mostly propagation delay and clock difference due to small frequency offsets in the sources. Some error can occur because of ionospheric refraction and propagation of the signal through receiver components. NTS/TTR measurements are taken when the satellite is at its time of closest approach (TCA) in order to minimize the effect of ionospheric refraction. The remaining error due to refraction is deemed insignificant for time transfer applications. Propagation delay in the receiver is constant for each tone and is calibrated out at the receiver. The output of the receiver then becomes the combination of propagation delay and clock difference which is used in the time transfer method to obtain a clock difference between a central station and the station where the NTS/TTR is located.

The receiver consists of three subsystems, each employing different types of electronics. The RF subsystem is comprised of analog electronics, the function of which is to acquire and track the satellite signal, mix the synthesized tones with the received tones, and provide an output which contains tone phase difference information. The digital processing subsystem is comprised of transistor-transistor logic (TTL). It synthesizes sidetones, contains a real-time clock, samples phase information from the RF subsystem output, and provides the phase samples to the microprocessor subsystem. The microprocessor subsystem is a microcomputer which controls the overall operation of the receiver.

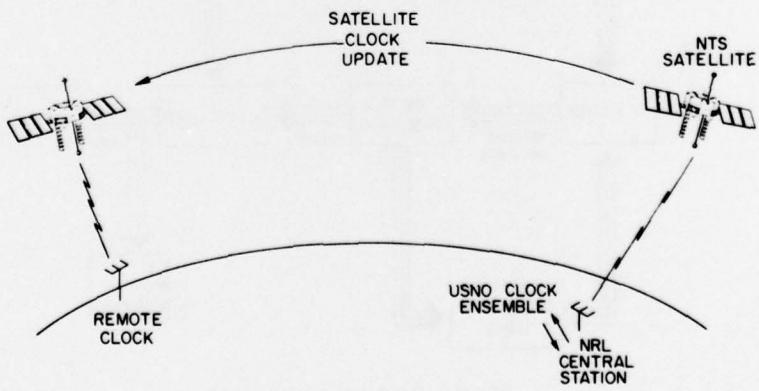


Fig. 1 -- Time transfer configuration

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It tunes the RF station, provides the man-machine interface, and processes the sampled phase of the digital subsystem to obtain satellite range. The range is displayed on the front of the receiver and is also output digitally so that an automatic recording device might be used. Figure 2 is a functional block diagram of the receiver.

RF Subsystem

The NTS signal used by the TTR has the format shown in Fig. 3. The receiver is capable of operating in two modes. In the "carrier" mode, the continuous carrier is tracked and the receiver is tuned manually for acquisition. In the "reference" mode, the offset reference sidetone is tracked and the receiver is automatically tuned by the microprocessor for quick acquisition since the signal is only present for 5.5 or 7.5 s. The RF subsystem uses a frequency-tracking phase-locked loop to generate coherent internal signals which mix the sidetones down to a signal consisting of range tones + 30 kHz + range-tone doppler. Tones synthesized by the digital subsystem are then used to convert this signal to the 30 kHz + range-tone doppler which is sampled by the digital subsystem. The RF subsystem also outputs the following to the digital and microprocessor subsystems:

- i. an indication that the tracking loop has acquired the signal,
- ii. a short-pulse signal indicating each time the tracking loop loses lock, and
- iii. the tracking-loop voltage-controlled crystal oscillator (VCXO) frequency.

For purposes of verifying proper functioning of the receiver, the RF subsystem can insert calibration tones into the sidetone channel. These are generated from the tones synthesized in the digital subsystem. A simplified block diagram of the RF subsystem is shown in Fig. 4.

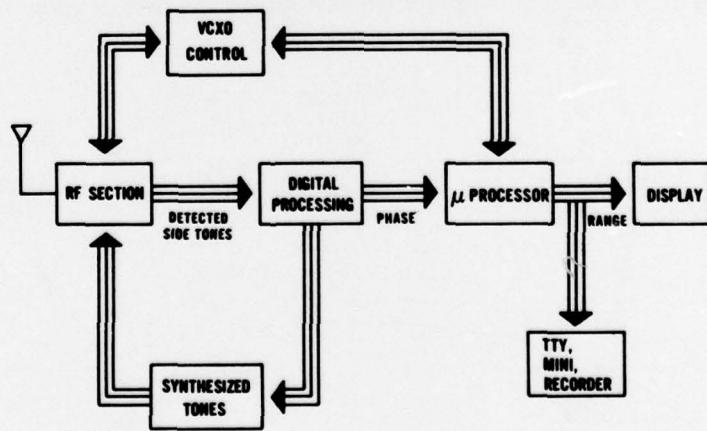


Fig. 2 — Rx functional diagram

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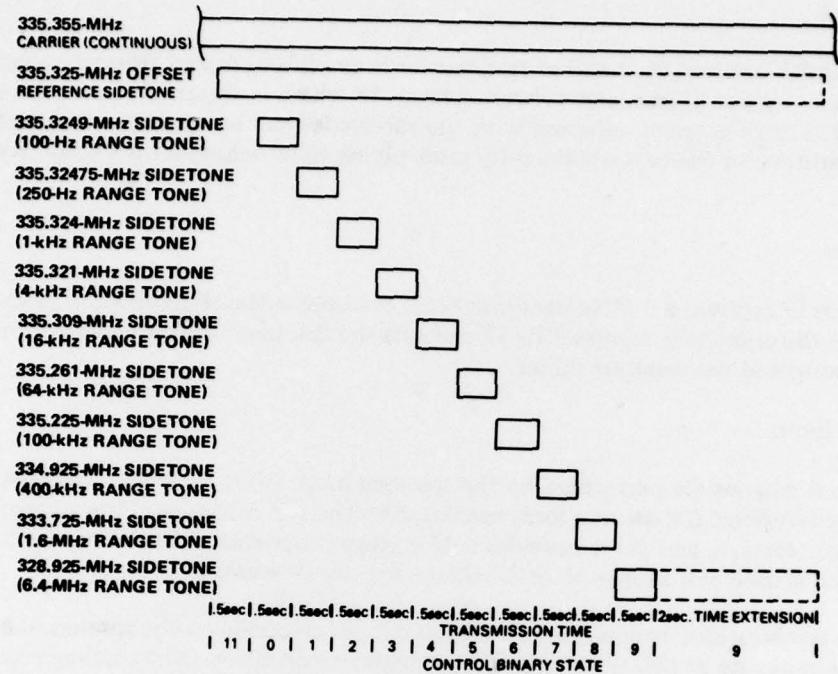


Fig. 3 — NTS signal patterns

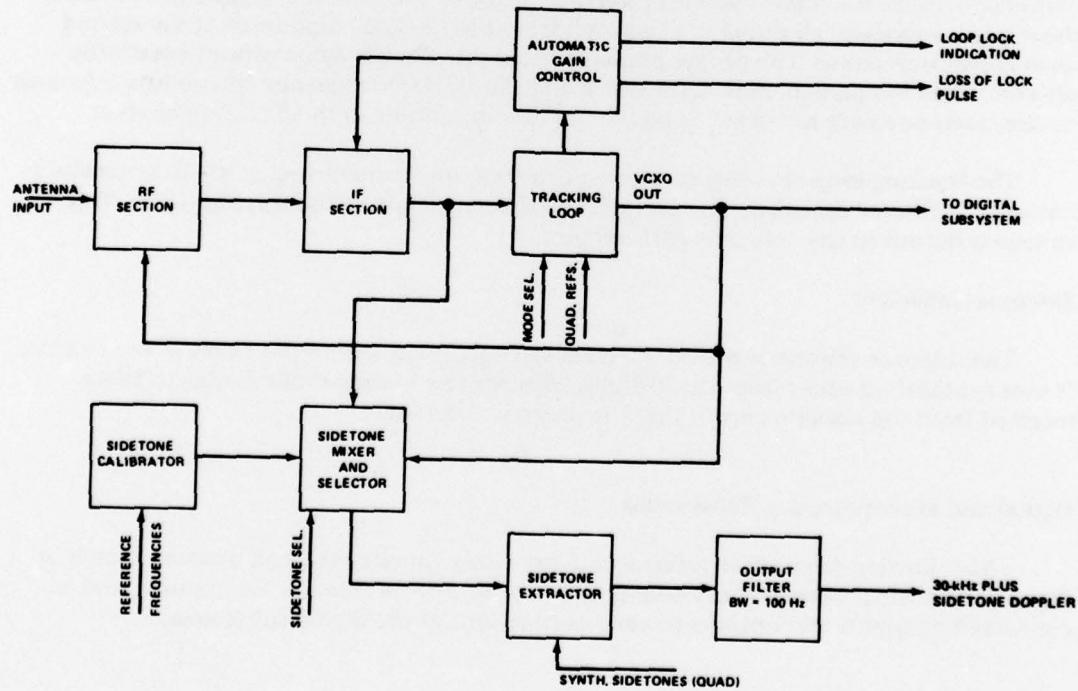


Fig. 4 — RF subsystem

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RF Section

In the RF section, the band of frequencies is amplified, passed through an image and interference-rejection filter, and converted to an IF which is about one-tenth the received frequency. The IF remains coherent with the received signal because the local oscillator for the first conversion mixer is obtained by multiplying the tracking-loop VCXO frequency by nine.

IF Section

In the IF section, a 9-MHz bandpass filter establishes the IF bandwidth, and AGC is applied to the composite signals. The IF outputs the full band of frequencies to both the tracking loop and the sidetone mixer.

Tracking Loop

Two functions are performed by the tracking loop: (a) it provides a coherent frequency reference for use as a local oscillator by the RF section and the sidetone mixer and selector section, and (b) it provides a dc voltage proportional to the received signal level which is used as a source of AGC voltage for the IF section.

The tracking loop is configured to track either the carrier or the reference frequency by selection of one or two narrow-passband predetection filters. The tracked component is then downconverted a second time, amplified, and applied to the loop phase detector whose output controls the VCXO. The VCXO output is used as the local oscillator for the second conversion. Since the phase-detector reference is one of two coherent signals generated by the digital subsystem, all doppler is removed from the tracked component at the second downconversion mixer. The proper phase-detector reference frequency is automatically selected when the predetection filter is selected. The VCXO frequency is used as a reference by the sidetone-mixer and selector section and is also output to the digital subsystem.

The tracking-loop circuitry contains a coherent amplitude detector which generates a low-level unfiltered dc voltage proportional to the amplitude of the tracked signal. This voltage is output to the coherent AGC section.

Sidetone Calibrator

The sidetone calibrator provides a means of supplying calibration tones in the receiver. It uses synthesized tones from the digital subsystem to generate tones similar to those received from the satellite except that the phase is constant.

Digital and Microprocessor Subsystems

The following description refers to the processor functional block diagram shown in Fig. 5. The microprocessor subsystem is shown as one block, the microcomputer, and is connected by inputs and outputs to various functions of the digital subsystem.

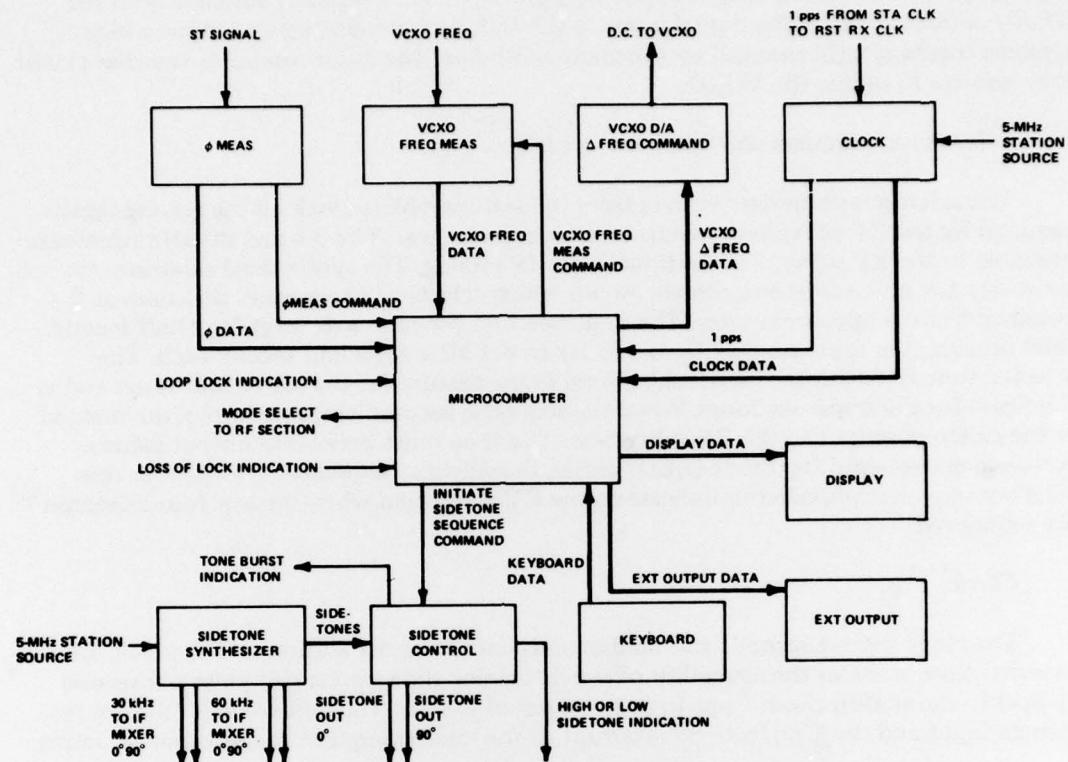


Fig. 5 — Processor

Digital Subsystem Functions

The digital subsystem is primarily TTL logic design which performs hardware functions for the microcomputer. The functions are described as follows.

Phase Measurement

The signal input to the processor from the RF subsystem is at 30 kHz and contains the doppler of the sidetones. The phase of this signal is measured by a time-interval counter at the command of the microcomputer. The data are input to the microcomputer upon conclusion of the measurement.

VCXO Control

The microcomputer has the capability of controlling the VCXO frequency through the use of a frequency measurement counter and a digital-to-analog converter. Upon command of the microcomputer, the frequency measurement counter counts the number of VCXO cycles which occur in 1 s. These data are made available to the microcomputer after the 1-s

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measurement. The analog output of the D/A converter is continually summed with the VCXO control voltage. The digital input to the D/A is controlled by an output which remains constant until changed by the microcomputer. The microcomputer thus has closed-loop control in tuning the VCXO.

Sidetone Synthesizer and Sidetone Control

The sidetone synthesizer derives from the station 5-MHz clock all the mixing signals required by the RF subsystem to extract the desired signal. The 30- and 60-kHz signals are available to the RF subsystem continually for IF mixing. The synthesized sidetones are continuously fed into a sidetone control circuit which selects and sequences the tones at the command of the microcomputer. The sequence first provides a dc level for a half second, then provides ten tones ranging from 100 Hz to 6.4 MHz for a half second each. The selected tone is output to the RF subsystem in quadrature for the lower four tones and in duplicate for the upper six tones. When the sequence is complete, a dc level is maintained at the sidetone output to the RF subsystem. The tone-burst indication output lights a front-panel light-emitting diode (LED) during the sidetone sequence. The high- or low-sidetone output is provided to indicate to the RF subsystem when the low four sidetones are sequenced.

Clock

The clock derives seconds and milliseconds data from the station 5-MHz clock. An external reset provides the capability of synchronizing the receiver one pulse per second (1 pps) to the station clock 1 pps to an accuracy of 200 ns. The milliseconds data are fed into an input and the 1 pps into an interrupt of the microcomputer for real-time updating.

Mode Select, Loop Lock, and Loss of Lock

The mode-select output is an indication to the RF subsystem and front-panel LED as to whether the carrier or reference mode of the receiver has been selected. The loop-lock indication is an input from the RF subsystem and is active whenever the receiver is locked on a signal. The loss of lock is another input from the RF subsystem that provides a pulse whenever the receiver loses lock.

Keyboard, Display, and External Output

A 16-button hexadecimal keyboard inputs data to the microcomputer. The additional input functions "interrupt," "clear," "enter," and "continue" are provided by a 4-button keyboard. A 32-character alphanumeric gas-discharge display outputs data and messages to the operator. The external output duplicates all data and messages that appear on the display, and is intended to be used in interfacing the receiver with an external device.

Microprocessor Subsystem Functions

In addition to controlling the various digital functions which interface the processor to the RF subsystem, the station clock, and the operator, the microcomputer processes the sampled data to obtain the phase of the sidetones and the observed range to the satellite.

Phase Determination

The receiver's primary mode of operation for processing data is in the reference mode using automatic acquisition. This is the mode in which the data processing will be described. First, the microcomputer waits until the time at which the tones are transmitted. While waiting, it holds the VCXO at the desired initial acquisition frequency previously entered as a prediction. When the tone transmission occurs, the VCXO D/A output is left at its last value and the synthesized tone-burst sequence is initiated in the receiver. The microcomputer begins to sample the phase of the first tone through the phase measurement circuit. For each tone, 81 samples of phase are taken at a 200-Hz rate, and a linear least-squares fit is made to these points. In this fit the following equation is realized:

$$\theta_i = M_i t_i + B_i \quad (1)$$

where θ_i is the phase of the i th sidetone, M_i is the phase rate of the i th sidetone, B_i is the phase of the i th sidetone at the time its sampling was begun, and t_i is the time of the phase relative to when the sampling was begun. Time is normalized to one unit equaling 5 ms for simplicity. In Eq. (1), the values of M_i and B_i are calculated from the least-squares approximation as follows:

$$M = \frac{S_0 S_4 - S_1 S_3}{S_0 S_2 - S_1^2},$$

$$B = \frac{S_2 S_3 - S_1 S_4}{S_0 S_2 - S_1^2},$$

where

$$S_0 = \text{number of samples} = 81,$$

$$S_1 = \text{sum of the times for each sample}$$

$$= 0 + 1 + 2 + 3 + \dots + 80$$

$$= 3240,$$

$$S_2 = \text{sum of the times squared for each sample}$$

$$= 0^2 + 1^2 + 2^2 + 3^2 + \dots + 80^2$$

$$= 173,880,$$

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S_3 = sum of the phases including integer wavelengths as measured from the time of the first sample,

S_4 = sum of the phases multiplied by the sample times.

Substituting for the constants that result from fixing the number of samples and sample time gives

$$M = 0.00002258 S_4 - 0.0009033 S_3, \quad (2)$$

$$B = 0.0484 S_3 - 0.0009033 S_4. \quad (3)$$

The values of S_3 and S_4 are accumulated during the sampling of each tone, and B_i is calculated and saved for each tone. Since M_i is the phase rate of each tone due to doppler, if the doppler is assumed to be constant throughout the tone-burst sequence, then all of the tone phase rates are equal to the phase rate of the highest tone multiplied by a constant as follows:

$$M_i = K_i M_{10}, \quad (4)$$

where K_i is a constant unique for each tone, and M_{10} is the phase rate of the 6.4-MHz tone. M_{10} is calculated and saved for the 6.4-MHz tone.

In determining range, the phase of each sidetone is projected to the point in time that the range is desired. Equations (1) and (4) may be combined to give

$$\phi_i = K_i M_{10} t_i + B_i. \quad (5)$$

The ϕ_i in Eq. (5) must be corrected for propagation delay through the receiver, so an error term is added giving

$$\phi_i = K_i M_{10} t_i + B_i + \phi_{Ei}, \quad (6)$$

where ϕ_{Ei} is the calibration error. Equation (6) is used to determine the phase of each sidetone at the end of the tone burst, and these in turn are used to determine a range.

Range Determination

The determined phase differences represent propagation delay and clock error between the satellite clock and the receiver clock. These phases are interpreted in terms of observed range to the satellite in milliseconds. The phases of the lower tones are used to get a rough range and those of the higher tones are used to resolve range to nanosecond accuracy. In resolving range, Eq. (7) is used:

$$R_i = \frac{\phi_i + \text{INTEGER} [R_{i-1} f_i + 1/2 - \phi_i]}{f_i}, \quad (7)$$

where

θ_i is the phase of the i th tone,

f_i is the frequency of the i th tone,

R_i is the range in seconds whose accuracy is based on the phase of the i th tone.

The phase of each tone is determined to a resolution of 1%. The resolved range based on the phase of a tone is 1% of the tone's period. Therefore the resolution of the final range is 1% of the 6.4-MHz tone period or 1.56 ns.

After the range is calculated, the phase of each tone may be displayed as well as range if the operator desires. After displaying the phases, real time and the last range are continually displayed until the next sequence of data is processed.

OPERATION

The receiver is shown in Fig. 6. Inputs required are 1 pps and 5 MHz from the station clock. The receiver's final output is observed range to the satellite in milliseconds. These data are displayed on the front panel and also appear at an external output which may be interfaced with a teletype, minicomputer, or data recording device.

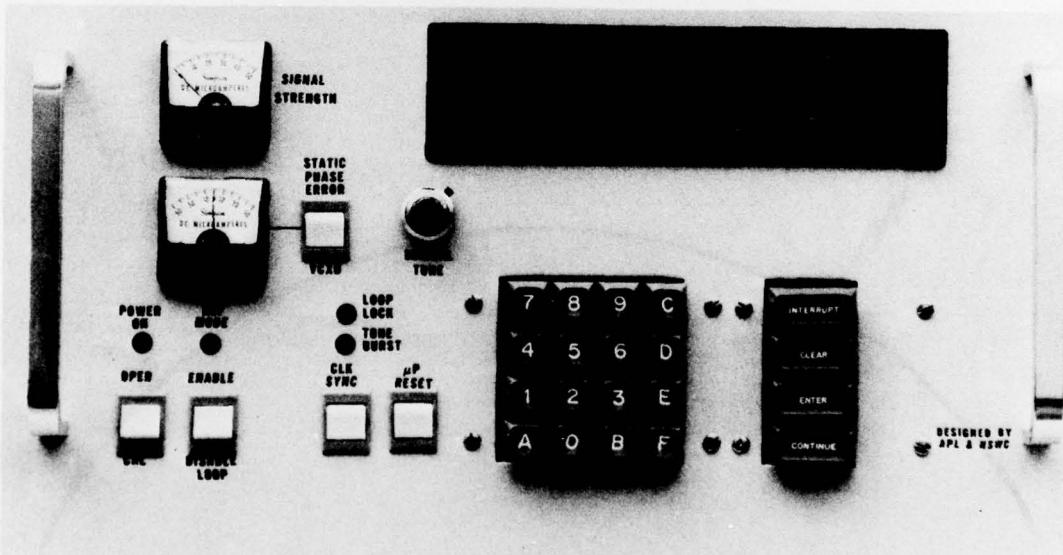


Fig. 6 — NTS/TTR

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When the receiver is initialized, the operator first synchronizes the receiver clock with the station clock, enters a predicted satellite frequency which is maintained by the microcomputer, and then waits for acquisition of the satellite signal. During the tone burst, if there is an affirmative lock indication, the VCXO frequency is measured and replaces the initial frequency input by the operator. The VCXO is held to this frequency by microcomputer control until time for the next burst of data. Again, upon lock of the signal, a new frequency is measured and the sequence continues, enabling the receiver to track the satellite throughout its doppler range. The microcomputer continues the sequence of taking data until interrupted by the operator.

FIELD TEST

A prototype receiver like the one shown in Fig. 6 was taken to a NASA tracking station at Rosman, N.C. A time transfer was performed as the configuration shows in Fig. 7. Time at Rosman was compared to that at an NRL tracking station at Chesapeake Beach, Md. Time at the NRL site was known relative to USNO time by portable clock measurements. In performing the time transfer, a range observation was made at Rosman and at Chesapeake Beach. The observation at Rosman was corrected for oscillator drift in the satellite clock during the time between the two measurements (5 - 8 min). The observation at Chesapeake Beach was corrected to USNO time, and the difference between the two stations was computed.

Figures 8 and 9 show one particular satellite pass with observations made at Rosman and Chesapeake Beach during the test. The data used in the time transfer were taken at the time of closest approach, and are pointed out with arrows. Twelve such passes were taken, and

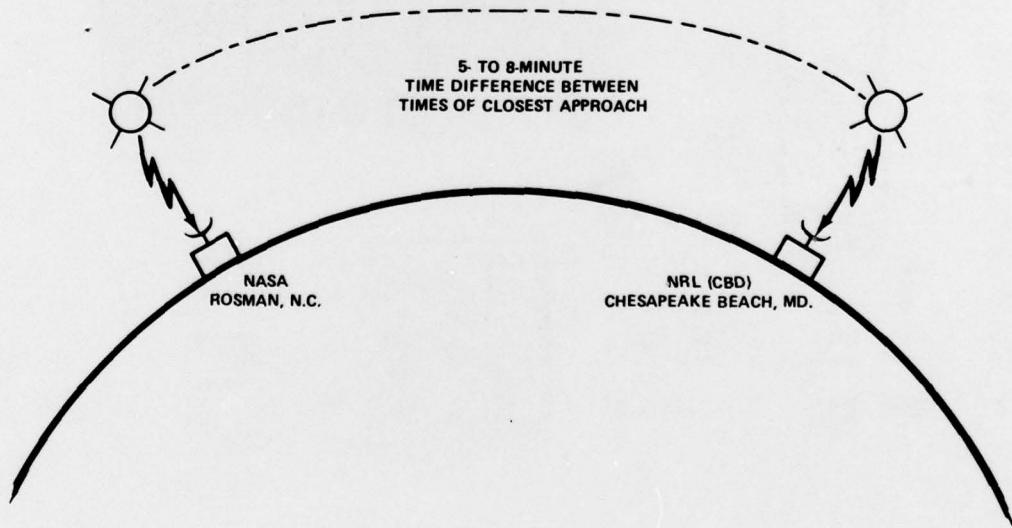


Fig. 7 — Time transfer with Rosman

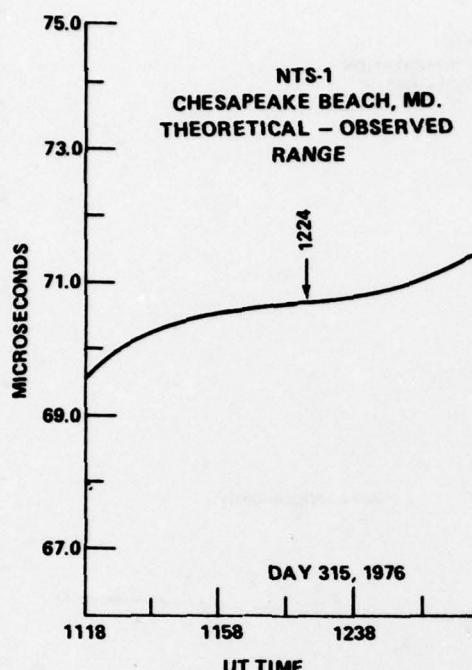


Fig. 8 — Chesapeake Beach pass

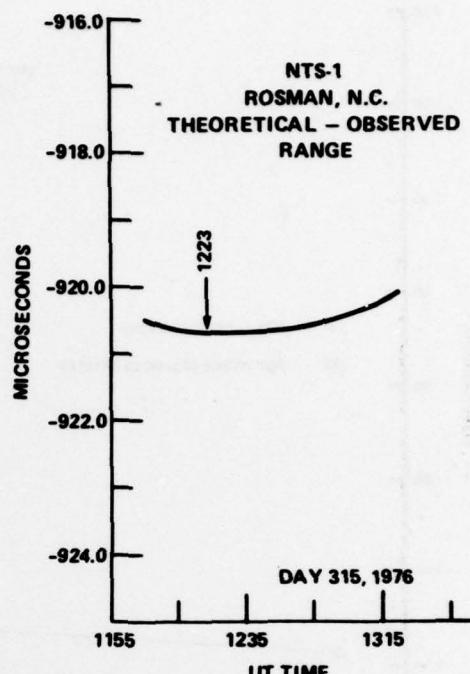


Fig. 9 — Rosman pass

each time transfer is plotted in Fig. 10. The data have an RMS fit of 86 ns. A portable clock measurement was made before and after the field test. These points are plotted, and a line drawn between the two falls very close to the time transfer data. The conclusion of the test is a time transfer accuracy better than 100 ns.

ACKNOWLEDGMENTS

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Mr. Paul Landis of NRL and Mr. Larry Raymond of the Naval Surface Weapons Center Dahlgren Laboratory assisted in the NTS/TTR design; Mr. Hugh Warren of Bendix Field Engineering Corporation aided in analyzing the data and obtaining time transfer results.

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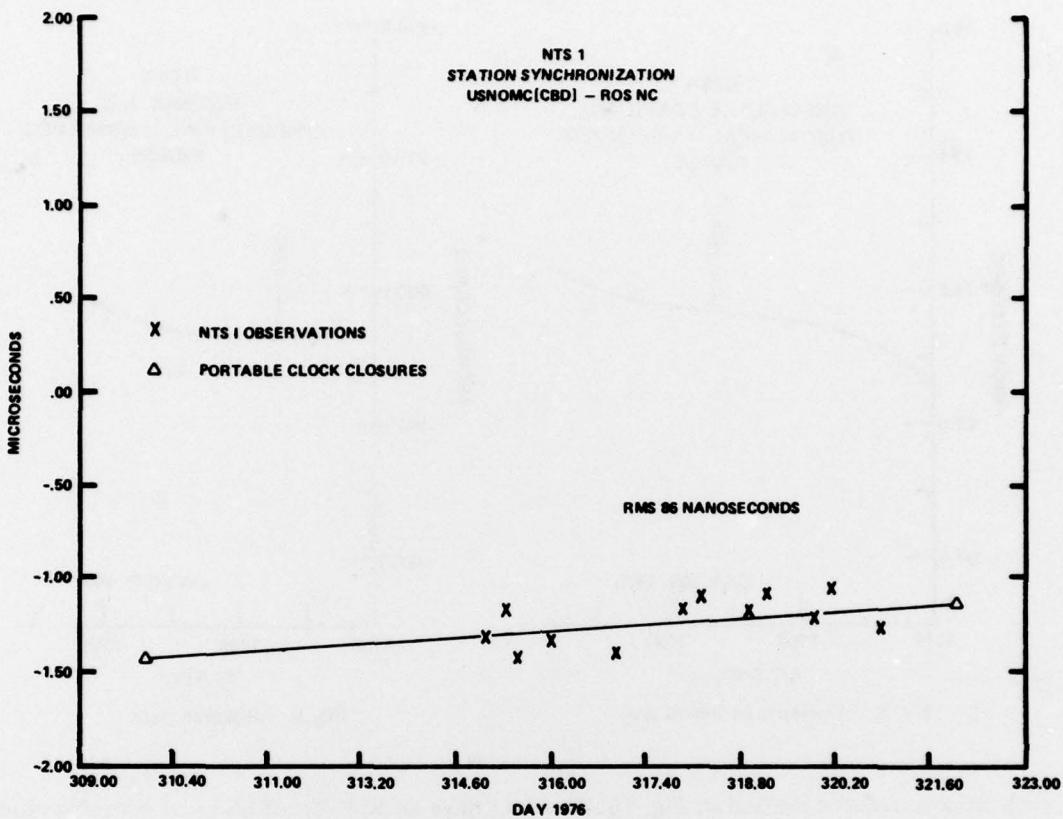


Fig. 10 — Time transfer results

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